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METHOD FOR DETERMINATION OF DESIGN PARAMETER FOR CORNERING LINKAGE OF SEMITRAILER WHEELS (1) EXPERIMENTAL RESEARCH ON THE OPERATION OF STEERING LINKAGE (2)

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Abstract: 1) Discussion of basic mathematical parameters of cornering a semitrailer with steerable wheels as related to the basic kinematic parameter. Major example given is cornering when tractor moves along a circular trajectory and semitrailer is still on the straightaway with subsequent conjugation.

This second

2) This article discusses specific theoretical and practical kinematics of steering linkage in terms of cornering angles. A measuring device using electro-mechanical time and course sensors is used in tests performed on a fork-lift truck. Measuring device described and test results given in bar graph and cumulative curve.

NOTICE

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A basic requirement for cornering linkage of steerable semitrailers is the safeguarding of trajectory coincidence of the tractor and semitrailer when cornering the vehicle. In order that the linkage fulfills this need there must be a correct design of the drive mechanism (for example, the cam surface) for which it is necessary to know the basic structural kinematic parameter, that is, the function

$$\varphi_{\text{п}} = f(\gamma), \quad (1)$$

where $\varphi_{\text{п}}$ - reduction angle of cornering of semitrailer wheels;

γ - angle of vehicle fold.

In a published study[1] the method for determining the relationship (1) is shown during motion of the vehicular units along a trajectory whose function is

$$y = f(x). \quad (2)$$

In practice, during the process of cornering the vehicle with a steerable semitrailer there inevitable occur certain positions of the vehicular units when the tractor moves into a trajectory whose function is $y_1 = f(x_1)$, and the semitrailer must be moved into another trajectory by which the vehicle was

[1] Kryshen', N. I., Avtomobil'naya Promyshlennost', 1968, No. 6.

earlier moved. We will designate the function of this trajectory as $y = \varphi(x)$. After the semitrailer reaches the conjugation point of functions $y = \varphi(x)$ and $y_1 = f(x_1)$, the semitrailer will begin to move into the trajectory in function $y_1 = f(x_1)$.

Presented in Fig. 1 is a schematic of vehicular motion during cornering when the vehicle, starting from point A, moves along the trajectory in function $y_1 = f(x_1)$, and the semitrailer moves along the trajectory in function $y = \varphi(x)$ (earlier course of the vehicle) up to point A. In this case the basic structural kinematic parameter of the cornering linkage of the wheels will depend both on function $y_1 = f(x_1)$ and on function $y = \varphi(x)$.

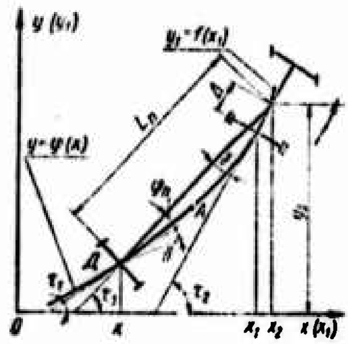

Fig. 1: Schematic of motion of vehicle with steerable semitrailer in cornering when the tractor moves along the trajectory in function $y_1 = f(x_1)$, and the semitrailer along the trajectory in function $y = \varphi(x)$.

In the aforementioned study the method for determining the basic structural kinematic parameter of the linkage is discussed when the tractor and semitrailer move along the trajectories of various functions.

From Fig. 1 it follows that

$$x_1 + \frac{\Delta}{\sqrt{1+\left(\frac{dy_1}{dx_1}\right)^2}} = x + l_n \cos \tau_0;$$
$$y_1 + \frac{\Delta \frac{dy_1}{dx_1}}{\sqrt{1+\left(\frac{dy_1}{dx_1}\right)^2}} = y + l_n \sin \tau_0, \qquad (3)$$

from which

$$\left[\left(x_1 + \frac{\Delta}{\sqrt{1+\left(\frac{dy_1}{dx_1}\right)^2}}\right) - x\right]^2 + \left[\left(y_1 + \frac{\Delta \cdot \frac{dy_1}{dx_1}}{\sqrt{1+\left(\frac{dy_1}{dx_1}\right)^2}}\right) - y\right]^2 = l_n^2. \qquad (4)$$

Equation (4) allows a determination of the coordinates of point Д (x,y), and consequently a determination of the position of the semitrailer on a trajectory whose function is $y = \varphi(x)$ at that moment when the tractor moves along the trajectory in function $y_1 = f(x_1)$.

From Fig. 1 it follows

$$\gamma = \tau_2 - \tau_0; \quad \varphi_n = \tau_0 - \tau_1, \qquad (5)$$

where

$$\tau_1 = \operatorname{arctg} \frac{dy}{dx};$$
$$\tau_2 = \operatorname{arctg} \frac{dy_1}{dx_1};$$

τ_0 is determined from the system of equations (3).

With a calculation of lateral elasticity of the tires on the steerable wheels of the semitrailer, equation (5) takes the form

$$\gamma = \tau_2 - \tau_0; \quad \varphi_n = \tau_0 - \tau_1 - \delta_1. \qquad (5a)$$

where δ_1 is angle of lateral climb of the semitrailer tires.

Equations (5) and (5a) are obtained for determining angles γ and $\varphi_{\text{п}}$, that is, for determining the relationship (1) during motion of the vehicular wheels along the given trajectory. Thus, through angles τ_0, τ_1, and τ_2 is revealed relationship (1), which occurs with the basic structural kinematic parameter for determining the characteristics of the drive mechanism. For example, determining the profile of the cam surface slot, securing the direction of the turning linkage of the semitrailer wheels so that the trajectory of the semitrailer and tractor will coincide during movement of the tractor along a given trajectory.

We will apply the above-mentioned analytical method for determining relationship (1) in a concrete situation of vehicular motion in cornering. We will assume (Fig.2) that the tractor with previously turned wheels at a determined angle goes into the turn along a circle, and the semitrailer must still move along the straightaway.

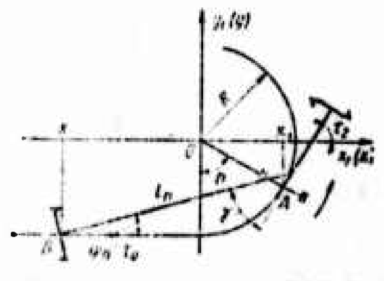

Fig. 2: Schematic of vehicular motion with a steerable semitrailer when cornering, the tractor moving along a circle and the semitrailer along the straightaway.

In this case the equations (5) take on the form

$$\varphi_{\text{п}} = \arcsin\left(\frac{R}{L_{\text{п}}} + \frac{y_1}{L_{\text{п}}} - \frac{A}{L_{\text{п}}} \cdot \frac{x_1}{R}\right);$$
$$\gamma = -\operatorname{arctg}\frac{x_1}{y_1} - \varphi_{\text{п}}. \qquad (6)$$

Values of the angles $\varphi_{п}$ and γ are expressed through angle with the following relationships

$$\varphi_{п} = \arcsin\left[q(1 - \cos\tau_2) - k\sin\tau_2\right];$$
$$\gamma = \tau_2 - \varphi_{п}, \qquad (6a)$$

where

$$q = \frac{R}{L_{п}}; \quad k = \frac{\Delta}{L_{п}}.$$

In Fig. 3 the graphs show relation $\varphi_{п}$ from γ where $q_1 = 1.5; q_2 = 1; q_3 = 0.5$; and $k = 0.01$, obtained according to equations (6a).

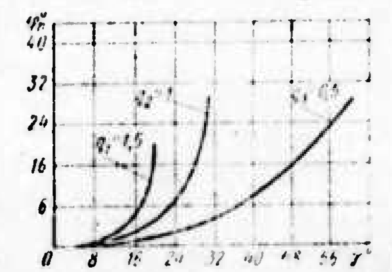

Fig. 3: Graphs of the relationship between angles $\varphi_{п}$ and γ during movement of the tractor along a circle and the semitrailer along the straightaway.

When the semitrailer comes to the point of conjugation of the straightaway with the circle, quantities γ and $\varphi_{п}$ become constants and are determined by the relationships

$$\varphi_{п.у} = \arcsin\frac{L_{п}^2 - \Delta^2}{2L_{п}R};$$

$$\gamma_у = \operatorname{arctg}\frac{BK\sqrt{R^2 + \Delta^2 - BK^2} - R\cdot\Delta}{R^2 - BK^2},$$

where $\gamma_у$ and $\varphi_{п.у}$ - angles γ and $\varphi_{п}$ under an established cornering of the vehicular wheels;

$$BK = \frac{L_{п}^2 + \Delta^2}{2L_{п}}.$$

The assumed method allows a determination of function $\varphi_{п} = f(\gamma)$ which occurs with the basic structural kinematic parameter during planning of the drive mechanisms, providing

trajectory coincidence of the tractor and semitrailer during movement of the tractor along a given transitory trajectory.

EXPERIMENTAL RESEARCH ON THE OPERATION OF STEERING LINKAGE

The steering linkage configuration is one of the important factors ensuring steerability of a wheeled vehicle and stability of its movement. A vehicle with improperly constructed or poorly adjusted steering linkage arbitrarily changes its direction of movement, "roams" along the road, which results in unnecessary wear and tear on the driver and a reduction of road safety. Improperly constructed linkage leads to wheel climb, slippage of the tires along the mounting surface and, as a result, wear on the tread. When designing a steering linkage one must provide for the kinematic condition of cornering the vehicle. For a vehicle with tires that are rigid in transverse direction this condition is expressed by the well-known formula

$$\operatorname{ctg}\theta_{н} - \operatorname{ctg}\theta_{в} = \frac{M}{L}, \qquad (1)$$

where $\theta_{н}$ - cornering angle of the outer steerable wheel;
$\theta_{в}$ - cornering angle of the inner steerable wheel;
M - spacing among the eight bolts in m;
L - wheelbase of the vehicle in m.

For a vehicle with tires that are elastic in transverse direction, relation of the angles θ_H and θ_B depends not only on quantities M and L, but also on the speed of the vehicle, total weight, its distribution among the eight bolts, the coefficients of resistance to climb, and other factors. And therefore, correlation of angles θ_H and θ_B is expressed by a considerably more complicated relation, although in most cases it can be successfully reduced to the formula according to the composition in the analogous expression (1).

A difficulty in designing the steering linkage and determining its configuration can also be concluded from the fact that for a steering linkage it is impossible to completely fulfill equation (1). The actual relation of the cornering angles provided by a steering linkage of the conventional form is expressed by the formula

$$\sin(\varphi - \theta_H) = \frac{BC}{A^2 + B^2} - \sqrt{\left(\frac{BC}{A^2 + B^2}\right)^2 - \frac{C^2 - A^2}{A^2 + B^2}}, \quad (2)$$

where

$$A = \cos(\varphi + \theta_B);$$

$$B = \frac{M}{m} - \sin(\varphi + \theta_B);$$

$$C = 1 - \frac{M}{m}\sin(\varphi + \theta_B) + \frac{M^2 - n^2}{2m^2};$$

- m - length of steering arm in m;
- n - length of tie-rod in m;
- φ - angle between the steering arm and longitudinal axis of the vehicle in a neutral placement of the linkage (Fig. 1a).

With established theoretical research fulfillment of the equation (1) is possible only with a ready-made jointed device with 14 sections. A steering linkage having all four sections always insures the regularity $\theta_H = f(\theta_B)$, coinciding with the stipulated requirements of cornering kinematics. The

discrepancy between the theoretical and actual relations increases with an increase in cornering sharpness (Fig. 1b) which leads to an additional increase of climb and a deterioration of the interaction of the tires with the mounting surface.

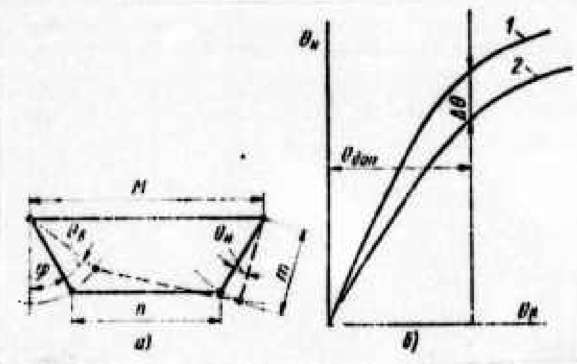

Fig. 1: Action of the steering linkage.

Key: a)- linkage schematic

b)- relation of the cornering angles of steerable wheels

1 - theoretical curve
2 - actual curve

In respect to structure it is fitting to mention linkage of that configuration which would insure acceptable conformity with the theoretical and actual values of θ_H in the interval of the best uses of values of angle θ_B. It is usually calculated that divergence $\Delta\theta$ at the limit of interval $\theta_{\text{доп}}$ must not exceed 2 - 3°. The actual application of the given criterion is made more difficult by the indefiniteness of the concept of interval $\theta_{\text{доп}}$, a quantity which depends on both the structure of the vehicle and on the conditions of its use.

With vehicles of long wheelbase moving along a road with a small quantity of obstacles (for example, inter-urban buses), the range of variation in cornering angles of steerable wheels is comparatively small. With vehicles of short wheelbase

operating under difficult conditions with a large quantity of sharp turns (light automobiles - taxis), this range is considerably more. Thus, in the design of steering linkage for new vehicles specially intended for operation under specific conditions, it is necessary above all to determine the limits of change of angles θ_H and θ_B during motion, and bring to light the best utilization of their values. However, investigations of this sort are not numerous, and their results are inconclusive and sometimes contradictory.

In the People's Republic of Bulgaria they are conducting a systematic study of the conditions of utilization of vehicles and their assemblies in accordance with the development plan for automotive industry and automotive transport. For increasing the stability and steerability of transport vehicles special methods were devised in the Scientific Research and Planning-Design Institute for battery-driven and motor trucks, allowing for quantitative characterization of operational conditions for steering linkage of wheeled vehicles. The attempts towards the goal of making good use of oscillographic equipment have proven unsuccessful, resulting from an unavoidable extraneous source of current with the stable voltage, high sensitivity towards vibration, bulkiness of disposition of the equipment in the vehicle, and great labor-consuming nature of deciphering the recordings. Therefore, there was suggested and prepared in the institute an original measuring device allowing study without preliminary processing of the total values of the figures. Such figures were obtained for the values of time and course of vehicular movement within various ranges of cornering angle values for steerable wheels.

The measuring device (Fig. 2) consists of a sensor for cornering angles 1 and electromechanical counters 2 and 3. The latter register impulses at a frequency of 10 Hz, since an impulse generator 4 is included in the circuit, sending

impulses at the stated frequency. In addition, for control the schematic includes a sensor with a counter 5, summarizing all impulses both for left turns and right turns. With the aid of this counter it is possible to determine the difference shown by the sums indicated by all the counters, giving the time in which the electro-sensor 1 was in isolated intervals. This time is subsequently necessary to take into account.

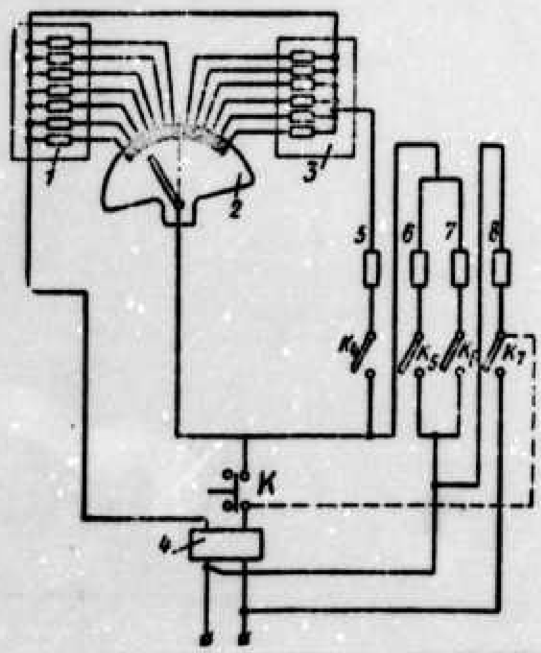

Fig. 2: Principle schematic of the measuring device.

The control sensor is located at an equal distance (considering angular displacement) from the second and last sensors of left and right turns, which eliminates errors in the measured results.

Counters 6 and 7 are connected to the individual sensors, but are not connected to the impulse generator, which allows a fix on left and right turns independent of time and course of motion. Course counter 8 is connected to the course sensor placed on the wheel of the vehicle. For switching off the time count when the vehicle is not moving but the wheels

remain in a turned position and the corresponding counter counts off the time impulses, a microswitch K is included in the schematic which breaks the circuit when the vehicle stops.

In the case of fixing course motion of the vehicle during various significant cornering angles, the impulse generator is switched off and the input terminal of microswitch K is connected to the output terminal of switch K_7 on the course sensor, as is shown in Fig. 2 by the dashed line.

The schematic elements have the following characteristics: impulse generator - IG; 12 volts; impulse frequency of 10 Hz; electromechanical counters - BE-1; output of 4 watts; microswitch - 80 am/K+E 171.

Construction of the cornering angle sensor is shown in Fig. 3. The frame 1 of the sensor made of mica is in segmented form. Along the periphery of the frame are milled grooves in which are mounted current-adjustable brass plates 2. Dimensions of the current-adjustable plates and their disposition on the frame are determined by the quantities of the turning ranges to left and right in relation to the neutral position of the linkage corresponding to linear motion of the vehicle. To the left are seven stipulated ranges, and six to the right.

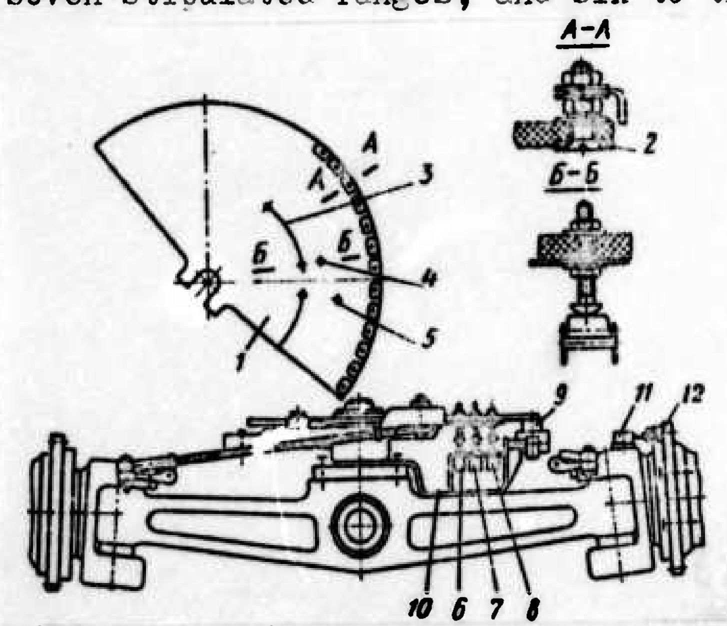

Fig. 3: General view and details of measuring device.

On the underside of the disc are placed sensor 3, summarizing all impulses, and also the sensors for left and right turns 4 and 5. Sensor 3 has a half-section shape, and sensors 4 and 5 are shaped in the form of brass screws with semi-spherical heads. Sensors 3, 4, and 5 are connected to microswitches 6, 7, and 8.

A graphite brush 9 and microswitches 6, 7, and 8 are placed under the disc and attached by means of a cleat 10 on the beam of the steering axle.

Course sensor 11 is mounted as well on the beam at one of the steerable wheels. The heads of bolts 12 connecting the rim of the wheel to the hub serve as contacts to close the circuit during rotation of the wheel. During one turn of the wheel it is possible to receive several impulses (corresponding with the number of bolts) which allows for an increase in accuracy of the course reading of the vehicle under study in a given range of cornering angles. During motion of the vehicle in a curve the cornering angle sensor of the steerable wheels, depending upon the dimension of the cornering angle corresponding to range, comes into contact with the brass plate through the stationary brush; the circuit is closed and the electro-contact counter fixes the quantity of impulses for each segment of time or course. The period of closed state of a given counter is determined by time period of vehicular motion corresponding to the range of wheel cornering angle.

For purposes of the tests a fork-lift truck was chosen, the performance of which is characterized by a great amount (more than a thousand changes) of turns in narrow passages along curves of small radiuses. The maximum cornering angles of the steerable wheels of the lifts allowed by structure amount to 80 - 85°.

With the fork-lift EV-676, assembled in series by

enterprises of the People's Republic of Bulgaria, lift capacity is 1 t, wheelbase 1.1 m, track of steerable wheels 0.63 m.

The fork-lift was tested under practical conditions during operation in a section of a paper pulp enterprise. The tests lasted several days, readings of the counters being recorded approximately every hour of fork-lift operation.

Results of the tests during operation of the measuring device were fixed by the sensors of time and course (Tables 1 and 2). After conversion of the sensor readings into angular quantities, the results of the recordings were processed according to a standard method of mathematical statistics. This allowed the construction of bar graphs of distribution of cornering angles of steerable wheels in relation to time of fork-lift motion and the studied course (Fig. 4a).

Table 1: Counter readings in fixing time of fork-lift motion.

Right counters						SUM COUNTER	Left counters							COURSE COUNTER	TIME IN MIN.
1	2	3	4	5	6		1	2	3	4	5	6	7		
4 533	[illegible]	289	84	15		3 872	1 [illegible]	976	230	[illegible]	7	—	—	14 511	60
7 881	[illegible]	528	[illegible]	[illegible]	143	7 235	[illegible]	[illegible]	532	218	[illegible]	57	—	[illegible] 012	50
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	11 655	7 [illegible]	[illegible]	816	[illegible]	[illegible]	67	37	[illegible]	60
15 016	[illegible]	[illegible]	450	[illegible]	[illegible]	13 605	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	105	37	[illegible]	60
17 [illegible]	[illegible]	[illegible]	644	[illegible]	[illegible]	15 765	11 [illegible]	[illegible]	[illegible]	[illegible]	[illegible]	105	37	[illegible] 313	60
26 561	[illegible]	[illegible]	657	[illegible]	[illegible]	19 649	12 [illegible]	[illegible]	1338	651	[illegible]	149	75	52 [illegible]	50

Table 2: Counter readings in fixing course movement of the fork-lift.

Right counters						Left counters							COURSE COUNTER	TIME IN MIN.
1	2	3	4	5	6	1	2	3	4	5	6	7		
3 722	538	163	52	7	1	977	405	110	38	2	—	—	14 219	75
6 565	624	338	100	13	3	2203	1103	378	127	20	22	—	41 191	75
14 516	1837	440	165	48	53	7663	1358	425	137	44	28	—	50 392	60
18 680	1901	706	280	81	78	9900	1432	577	159	68	10	5	66 480	75

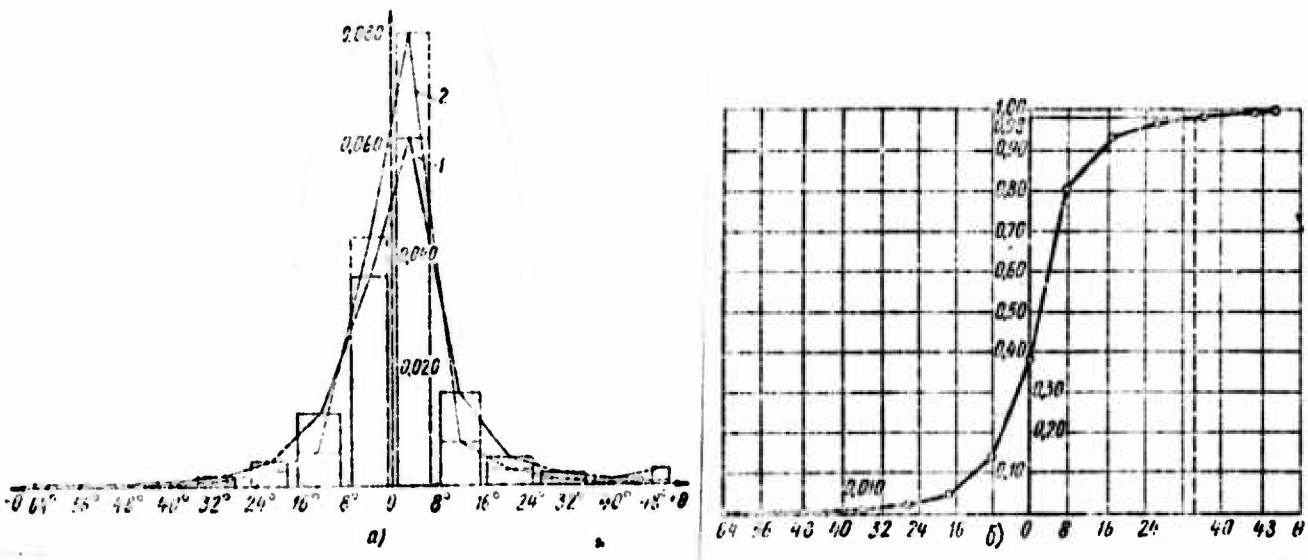

Fig. 4: Test results.

Key: a) Distribution graph
1 - according to time of motion
2 - according to studied course

b) Cumulative curve

The cumulative curve (Fig. 4b) allows a determination of time during which the linkage is located in the given range of cornering angles. Thus, in our case the fork-lift operates at 97% of aggregate time with cornering angle of steerable wheels not exceeding 34°30'. Maximal cornering angle of the inside wheel of the fork-lift under the tests amounted to 64°, which is a much smaller angle allowed by the structure of the steering linkage (85°30'). This data is the basis of new steering linkage structures being designed by the institute.

The tests verified the greater reliability and accuracy of the measuring device. The contact counters are simple in their installation, there is no danger of vibration and shock, and they need practically no maintenance. A comparison of the two possible methods of fixing (by time and by course)

has shown that they give identical types of relations, the processing of which is reduced to identical quantitative results.

The structure of the measuring device allows quick implementation of its assembly and disassembly. This facilitates utilization of the measuring device during the testing of machines of various makes and models.

At present the institute has begun research on the operation of steering linkage of freight vehicles.